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SUBSTITUTE SPECIFICATION

PLASMA PROCESSING APPARATUS AND PROCESSING METHOD

BACKGROUND OF THE INVENTION

The present invention relates to a plasma processing apparatus, which is equipped with a plasma generation means, and to a plasma processing method; and, more particularly, the invention relates to plasma etching suited to the formation of a minute pattern in a semiconductor device and liquid crystal display device and uniform processing of a large-diameter substrate, plasma CVD suited to the formation of a thin film having a minute structure, a plasma processing apparatus for plasma polymerization, and a plasma processing method.

In a plasma processing apparatus of the type which is used to produce a semiconductor device and a liquid crystal display device, for example, using a plasma, it is a requirement that the electric characteristics of the semiconductor device not be changed by control and treatment of the radical species affecting the processing performance, the energy and directionality of ions applied to the substrate to be processed, and the uniformity in plasma processing.

Regarding the control of radical species generation, Official Gazette of Japanese Patent Laid-Open NO. 195379/1996 discloses a plasma processing method characterized by excellent controllability of radical species generation by generation of plasma containing both capacitatively coupled and inductively coupled characteristics.

Ion energy control and ion directionality are mentioned in the Official Gazette of Japanese Patent Laid-Open NO. 158629/1985, which discloses a method of electronic cyclotron resonant discharge and the application of a radio frequency bias to a substrate supporting electrode. Official Gazette of Japanese Patent Laid-Open NO. 206072/1993 reveals a method of generating an inductively RF coupled discharge and application of radio frequency bias to a substrate supporting electrode. These methods have realized an improvement in the directionality of ions by generation of high density plasma at a low pressure and ion energy control by application of a radio frequency bias.

Regarding uniformity control, Official Gazette of Japanese Patent Laid-Open NO. 195379/1996 discloses that a plasma processing technique featuring excellent controllability of plasma density distribution is realized by generation of plasma containing both capacitatively coupled and inductively coupled characteristics.

Furthermore, regarding the control of the plasma processing uniformity, the Official Gazette of Japanese Patent Laid-Open NO. 283127/1986 discloses a technique in which the electrode to which radio frequency power is applied is split into multiple pieces, and power applied to each electrode is independently controlled, thereby improving the uniformity.

Official Gazette of Japanese Patent Laid-Open NO. 260596/1999 reveals a technique for controlling the plasma density distribution by controlling the electromagnetic wave

emission distribution.

One of the problems in treating a semiconductor device substrate using plasma is that the electrical characteristics of the semiconductor device are changed by electrical influence during plasma processing. Official Gazette of Japanese Patent Laid-Open NO. 3903/2000 discloses a technique for reducing the influence of plasma processing on the electrical characteristics.

To satisfy processing characteristics required for production of a semiconductor device and liquid crystal display device, mere ion energy control is not sufficient. Processing characteristics are greatly affected by radical species, and its general control method is to change the processing conditions, such as the plasma generating radio frequency power and pressure in the process chamber.

However, radical species control based on processing conditions is limited, and differences in processing performances cannot be covered merely by changing the processing conditions if the discharge method is different, as in the case of the electronic cyclotron resonant method, inductive RF coupled method, and the most popular parallel plate electrode method mentioned as prior art.

Thus, problems remain in that the processing performances realized by the parallel plate electrode method cannot be realized by the electronic cyclotron resonant method, inductively RF coupled method, etc.

The electronic cycrotron resonant method allows effective

acceleration of electrons to be achieved by resonance. Thus, the electron energy level is high, and processing is difficult when decomposition of the process gas is reduced. In the inductively RF coupled method, plasma of locally high density is formed by electromagnetic waves radiated from the antenna, and it is diffused upward. Thus, the electron energy level at the plasma generating portion is high, and the processing is difficult when decomposition of the process gas is reduced.

In the parallel plate method, by contrast, electron are accelerated on the sheath formed on the electrode surface and interface of the plasma, and the energy level is low. Thus, this method is suited to processing under the condition where process gas decomposition is reduced.

As described above, the electron acceleration mechanism in plasma is different depending on the discharge method, and this is the reason why the differences in performances of each method cannot be covered by processing conditions.

Another problem is how to ensure uniform processing of all of the substrates. To improve productivity, the diameter of the substrate to be processed has been increased from 150 mm to 200 mm, and the diameter tends to increase to 300 mm. According to the prior art, uniformity has been achieved by changing the processing conditions or by taking such similar means.

However, a change in processing conditions is insufficient, as described above, but this is one of the important means to control the radical species. This makes it

necessary to ensure a uniformity of control which ensures compatibility between processing conditions which implement optimum etching characteristics and film formation characteristics and uniformity in processing.

The techniques revealed in Official Gazette of Japanese Patent Laid-Open NO. 195379/1996 and Official Gazette of Japanese Patent Laid-Open NO. 283127/1986 are not sufficient in connection with the mutual independence between uniformity in plasma processing and the control of radical species generation, and in connection with the compatibility between uniformity control and low pressure processing. Furthermore, the plasma density distribution control method as disclosed in the Official Gazette of Japanese Patent Laid-Open NO. 260596/1999 is not sufficient in the plasma distribution control range. These are the problems of the prior art.

The electrical characteristics of semiconductor devices change when plasma is used to process these semiconductor device substrates due to electrical influence during plasma processing. This problem is caused by an uneven self-bias potential occurring to the sheath between the substrate under processing and the plasma.

To control the ion energy, radio frequency power is applied to the substrate supporting electrode. One of the major reasons for uneven self-bias potential is that radio frequency current distribution resulting from application of this radio frequency power becomes uneven on the substrate.

The self-bias potential control method disclosed in the

Official Gazette of Japanese Patent Laid-Open NO. 3903/2000 cannot control the self-bias potential distribution, and it is insufficient to reduce the changes in electrical characteristics.

Furthermore, higher integration of semiconductor devices and greater diameter of the substrate for production have made it necessary to develop a technique providing a better controllability than the prior art, e.g. higher selectivity with underlying material, higher performance in processed shapes, more uniform processing of large-diameter substrates, and less influence upon device characteristics.

Regarding uniformity in plasma processing, the following trend has been observed. As a result of the increased diameter of the substrates to be processed, the process gas for etching and CVD processing flows from the center of the substrate to the outer periphery, and the radical species concentration distribution and the deposition film distribution become apparent. This makes it difficult to ensure uniform processing on all surfaces of the large-diameter substrate.

To solve these problems, the factors disabling uniform distribution must be offset by other etching characteristic controlling factors. One of the controlling factors is the capability of adjusting the plasma distribution as a convex/concave distribution, independently of processing conditions, such as plasma generation power and pressure.

Radical species are generated by collision between

process gas and electrons in the plasma, and it is one of the factors which greatly affect the processing characteristics, such as selectivity, processed shape and film quality in etching and CVD processing by plasma. The generated volume and type of this radical species is determined by the status of the energy of the electrons in the plasma.

Furthermore, to protect against the influence of plasma processing upon the semiconductor device, distribution of the RF current flowing through the substrate must be controlled in order to control the self-bias potential distribution.

SUMMARY OF THE INVENTION

One object of the present invention is to realize a plasma processing apparatus and processing method which have a wide control range for the status of electron energy, independently of processing conditions and uniformity control, and which are capable of controlling radical species generation.

Another object of the present invention is to realize a plasma processing apparatus and processing method comprising a uniformity control means capable of independently controlling processing conditions, such as plasma generation power and pressure, said uniformity control means providing compatibility of plasma uniformity with radical species control, ion energy control and improved ion directionality by generation of low pressure/high density plasma.

A further object of the present invention is to realize a plasma processing apparatus and processing method comprising a

means for controlling the distribution of RF current flowing through the substrate, said means providing compatibility among plasma uniformity, radical species control, ion energy control and improved ion directionality.

To achieve said objectives, the present invention has the following arrangement.

(1) A plasma processing apparatus comprises a plasma processing gas supply means, an exhaust means in a plasma process chamber, a plasma generating means, and a means to process plasma using the generated plasma; said plasma generating means being characterized by further comprising an electromagnetic wave radiating means formed by displacement current and magnetic field forming means. Said electromagnetic wave radiating means further comprises a means for controlling the radio frequency displacement current flowing between the conductors by forming from each of multiple insulated conductors the electrode of said capacitatively coupled discharge means to which RF voltage is applied.

(2) A plasma processing apparatus comprises a plasma processing gas supply means, an exhaust means in a plasma process chamber, a plasma generating means, and a means for applying RF power to control the energy of ions applied to a substrate placed on a stage, wherein the facing electrode through which RF current due to said radio frequency power flows via the plasma is composed of multiple insulated conductors, and a means is provided to vary the impedance

between these conductors and ground.

(3) A plasma processing apparatus comprises a plasma processing gas supply means, an exhaust means in a plasma process chamber, a plasma generating means, and a means for applying RF power to control the energy of ions applied to the substrate placed on the stage. Said plasma processing apparatus further comprises a stage for applying said radio frequency power and a means of keeping the facing electrode separated from the ground, wherein RF current due to application of radio frequency power flows through said facing electrode via plasma.

(4) For uniformity, plasma distribution is controlled by controlling the distribution of the radiated electromagnetic wave power and controlling the radio frequency power supplied to plasma in a capacitatively coupled state from multiple conductors to the which radio frequency power is applied.

The mechanism for giving energy to the electrons in the plasma from the electric field of electromagnetic waves includes a method of direct acceleration in the electric field of electromagnetic waves by increasing the electromagnetic wave power (IPC: inductively coupled plasma). Another method included in said mechanism is to accelerate electrons by matching between the direction in which electrons are rotated by the magnetic field and the direction of the electric field of electromagnetic waves by application of a magnetic field (electron cyclotron resonance).

Energy is supplied by the former method when a magnetic

field is not applied. When a magnetic field is applied, an electromagnetic wave passes through plasma more easily, and energy is supplied by the latter method.

When the magnetic field is applied, the direction of electron motion is matched with the direction of the electric field of electromagnetic waves, if the frequency at which electrons are rotated by the magnetic field are matched with the frequency of electromagnetic waves (electron cyclotron resonant conditions). Accordingly, electrons are accelerated until they collide with gas molecules, thereby creating high energy. If magnetic field conditions disagree with electron cyclotron resonant conditions, the direction of electron motion gradually disagrees with the direction of the electric field of electromagnetic waves, and acceleration and deceleration of electrons are repeated.

As the magnetic field conditions disagree with electronic cyclotron resonant conditions, the maximum energy reached by the electrons is reduced. The electron energy becomes lower than that under electronic cyclotron resonant conditions.

As described above, control of the magnetic field conditions allows free control of the electron energy. This makes it possible to control the generation volume and type of the radical species produced by decomposition of process gas.

In the event of disagreement with resonant conditions, the maximum energy reached by electrons has the following relationship. The percentage of reduction of the maximum energy of the electrons with respect to the percentage of

disagreement of magnetic field conditions with the resonant conditions increases in direct proportion to the electromagnetic wave frequency. Under the conditions of 2.45 GHz, which is normally used, there is a sharp reduction of electron energy due to deviation from the electronic cyclotron conditions, and practical control is difficult. A practically controllable frequency range is from 200 MHz to 10 MHz.

Electron cyclotron resonance at a frequency of several tens of MHz to 300 MHz is disclosed in Oda, Noda, and Matsumura (Tokyo Institute of Technologies): Generation of Electron Cyclotron Resonance Plasma in the VHF Band: JJAP Vol.28, No.10, October, 1989 PP.1860-1862, and Official Gazette of Japanese Patent Laid-Open NO.318565/1994. The relationship between the state of electron energy and magnetic field strength is not described therein.

A means to emit electromagnetic waves was arranged in such a way that a displacement current was fed between insulated conductors and an electromagnetic wave is radiated by this displacement current. A resonant circuit having the same resonant frequency as the radio frequency to be applied, including the capacity formed between conductors, was formed between the conductors. Thus, resonant conditions were controlled, thereby controlling the displacement current and radiated electromagnetic wave power.

Multiple RF current conducting means are installed at the position opposite to the position where the substrate to be processed is mounted to ensure that control of the RF current

ratio flowing through said multiple RF current conducting means will be possible.

When there is no magnetic field, an electromagnetic wave will hardly progress in the plasma. Under this condition without a magnetic field, conditions close to resonance conditions are setup, and the radiated electromagnetic wave power is increased, thereby ensuring energy to be supplied to electrons in the plasma from the electromagnetic waves at a position close to where the electromagnetic waves are radiated. Under these conditions, electron energy becomes partially high at a position close to where the electromagnetic waves are radiated, and decomposition of the process gas proceeds. This makes it difficult to effect control at the state of low dissociation.

Under the condition where a magnetic field is applied, electromagnetic waves are likely to progress in the plasma. This allows energy to be supplied from electromagnetic waves into the electrons in the plasma over the entire space where plasma is generated. This leads to uniform distribution of electronic energy. Furthermore, the electron energy level is also made low, and control is effected in the state of low dissociation.

As under the condition without a magnetic field, if energy is supplied at a position close to where electromagnetic waves are radiated, a high density plasma is formed in this portion, and diffusion from this position allows plasma to reach the substrate to be processed. In such

a mechanism, therefore, diffusion is changed by pressure, and the plasma density and the plasma distribution on the substrate to be processed is affected by pressure.

By contrast, when a magnetic field is applied and energy is supplied over the entire space where plasma is generated, they are not affected by diffusion of the plasma. So, the plasma distribution is not easily affected by processing conditions, such as pressure. Such conditions are essential to control processing conditions and plasma distribution independently.

As a means of controlling the uniformity according to the present invention, multiple portions were provided where electromagnetic waves were radiated by a displacement current, and an arrangement was made to ensure that the amount of radiated electromagnetic waves could be controlled at least at one of said portions. The resonance conditions control method described above is used for this control. The portion radiating electromagnetic waves is provided in a double configuration to have a circular form, so that the plasma distribution can be controlled as a convex/concave distribution by controlling each radiated electromagnetic wave.

Furthermore, when the magnetic field is applied, plasma is generated over the entire plasma generation space. Then changes in the plasma distribution are less often caused by processing conditions, and plasma distribution control by control of resonance conditions can be effected independently

of processing conditions. Also, the generated volume and type of the radical species can be controlled by magnetic field, independently of the uniformity control and processing conditions.

If the conductor portion radiating electromagnetic waves is provided close to the plasma, the power can be supplied to plasma by capacitative coupling. Therefore, in accordance with the present invention, discharge can be made by the same capacitative coupling as that of the parallel plate electrode method under the conditions where resonant circuit current is reduced without the magnetic field being applied. An inductively coupled discharge due to electromagnetic wave emission is caused by increasing the resonant circuit current, and a discharge under electron cyclotron resonance conditions can be caused by application of a magnetic field.

A capacitatively coupled discharge, inductively coupled discharge and electronic cyclotron discharge each have different states of electron energy and different states of process gas decomposition. The present invention allows radical species to be controlled by controlling the discharge method, in addition to radical species control by magnetic field as described above.

The energy of the ions applied to the substrate placed on the stage is controlled by application of radio frequency power. Radio frequency current by this radio frequency power is fed to the facing electrode through the plasma.

To solve the problem that electric characteristics of the

semiconductor device are changed by electric influence during plasma processing, this facing electrode is composed of multiple insulated conductors, and the radio frequency current flowing through the substrate mounted on the stage is made uniform by optimization of the impedance between these conductors and ground. This has ensured a uniform distribution of self-bias potential on the substrate, and has reduced changes in the electric characteristics of the semiconductor device resulting from electric influence during plasma processing.

Also, the stage and facing electrode through which radio frequency current flows via the plasma are kept separated from the ground. This greatly reduces the percentage of radio frequency current flowing from the stage into the plasma by application of radio frequency power, with respect to that flowing to the conductor connected to the ground other than the facing electrode.

This allows almost all radio frequency currents to flow between the stage and the facing electrode. Also, the radio frequency current on the stage can be made uniform by installing the facing electrode parallel with the stage. This can reduce changes in electric characteristics of the semiconductor device resulting from electric influence during plasma processing.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic diagram representing a plasma processing apparatus representing a first Embodiment according

to the present invention;

Figure 2 is a schematic circuit diagram representing a resonant circuit model in the first Embodiment according to the present invention;

Figure 3 is a graph representing a plasma density distribution control in the first Embodiment according to the present invention;

Figure 4 is a graph representing a plasma density distribution control in the first Embodiment according to the present invention;

Figure 5 is a graph representing a plasma density distribution control in the first Embodiment according to the present invention;

Figure 6 is a graph representing the relationship between variable capacitor capacity and plasma density distribution uniformity in the first Embodiment according to the present invention;

Figure 7 is a diagram showing a radio frequency current path model based on application of radio frequency bias in the prior art;

Figure 8 is a diagram representing a radio frequency current path model based on application of radio frequency bias in the first Embodiment according to the present invention;

Figure 9 is a diagram representing the arrangement of a cover member representing a first Embodiment according to the present invention;

Figure 10 is a schematic diagram representing a plasma processing apparatus representing a second Embodiment according to the present invention; and

Figure 11 is a processing time diagram representing the progress of etching in the second Embodiment according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

A first embodiment of the present invention will be described with reference to Figs. 1-9 of the attached drawings. Figure 1 is a schematic diagram of a plasma processing apparatus representing the first Embodiment.

A process chamber 1 comprises inner wall surfaces 1a and 1b, and both inner wall surfaces are insulated from each other by an insulator 4c. Facing electrode 2a, 2b and stage electrode 3 are disposed therein in face-to-face relation with each other. The inner wall surfaces 1a and 1b are insulated from the facing electrode 2b by an insulator 4a and from the stage electrode 3 by an insulator (not illustrated). The facing electrodes 2a and 2b are insulated from each other by an insulator 4b.

Connections between the inner wall surface of the process chamber 1, the electrodes and the insulators are vacuum sealed. Refrigerant flow paths 5a and 5b, and the process gas supply paths 6a and 6b are provided inside the facing electrode. Refrigerant flow paths 5a and 5b are connected to a circulator (not illustrated) to ensure that the facing electrode temperature will be kept at a set value.

Process gas supply paths 6a and 6b are connected to the process gas supply source 27 so that process gas at the set flowrate can be supplied. Covers 8a, 8b, 8c and 8d are mounted on the surface of the facing electrode, and each cover forms a space of 0.2 mm with the adjacent cover.

Process gas is supplied to the back of the covers 8a, 8b and 8c through gas inlets 7a and 7b from process gas supply paths 6a and 6b. Passing through the 0.2 mm space between covers, the gas is fed to the process chamber 1.

The inner wall surface 1a is connected with a radio frequency power supply 18 and matching box 19. It is also connected with a high pass filter 20 in conformity to the frequency of the radio frequency power supply 9, so that radio frequency current from radio frequency power supply 9 is fed to the ground.

Facing electrode 2a is connected with radio frequency power supply 9 through matching box 10 and variable capacitor 11, and facing electrode 2b is connected with radio frequency power supply 9 through matching box 10 and inductors 12a and 12b.

Facing electrodes 2a and 2b are connected with low pass filters 13a and 13b in conformity to the frequency of the bias power supply 17, so that radio frequency current from the bias power supply 17 applied to the stage electrode 3 can be fed to a transformer 29 through facing electrodes 2a and 2b.

A coil 14 is provided on the outer periphery of the process chamber 1 so that a magnetic field intersecting at